A light stop and its consequences at the Tevatron and LEPII

JORGE L. LOPEZ[(a),(b)], D. V. NANOPOULOS[(a),(b),(c)], and A. ZICHICHI[(d)]

[(a)] *Center for Theoretical Physics, Department of Physics, Texas A&M University*
College Station, TX 77843–4242, USA
[(b)] *Astroparticle Physics Group, Houston Advanced Research Center (HARC)*
The Mitchell Campus, The Woodlands, TX 77381, USA
[(c)] *CERN Theory Division, 1211 Geneva 23, Switzerland*
[(d)] *CERN, 1211 Geneva 23, Switzerland*

ABSTRACT

An interesting prediction of a string-inspired *one-parameter* $SU(5) \times U(1)$ supergravity model, is the fact that the lightest member $(\tilde{t}_1)$ of the top-squark doublet $(\tilde{t}_1, \tilde{t}_2)$, may be substantially lighter than the top quark. This sparticle $(\tilde{t}_1)$ may be readily pair-produced at the Tevatron and, if $m_{\tilde{t}_1} \lesssim 130\,\mathrm{GeV}$, even be observed at the end of Run IB. Top-squark production may also be an important source of sought-for top-quark signatures in the dilepton and ℓ+jets channels. Therefore, a re-analysis of the top data sample in the presence of a possibly light top-squark appears necessary before definitive statements concerning the discovery of the top quark can be made. Such a light top-squark is linked with a light supersymmetric spectrum, which can certainly be searched for at the Tevatron through trilepton and squark-gluino searches, and at LEPII through direct $\tilde{t}_1$ pair-production (for $m_{\tilde{t}_1} \lesssim 100\,\mathrm{GeV}$) and via chargino and Higgs-boson searches.

The CDF collaboration has recently announced "evidence" for the existence of the top quark with mass $m_t = 174 \pm 17 \, \text{GeV}$ [1]. There exists also plenty of indirect evidence for the top quark from precise electroweak measurements at LEP [2], when contrasted with the corresponding theoretical calculations [3]. In the analysis leading to the possible discovery of the top quark, the Monte Carlo simulations which are compared with the data, assume the validity of the Standard Model, and no other processes beyond it contribute to the sought-for signal. In this note we would like to point out that, in the context of supersymmetric models, the pair-production of the lightest top-squark ("stop") may lead to very similar experimental signatures as the pair-production of top quarks. This fact by itself is not new, since it is well known that one can always adjust arbitrarily the parameters of the the Minimal Supersymmetric Standard Model (MSSM) to have a light top-squark [4, 5, 6, 7]. However, in the context of the minimal $SU(5)$ supergravity model [8], i.e., the simplest model underlying the MSSM, the constraints from the proton lifetime [9] force *all* the squarks to be heavier than the top quark. On the other hand, a light top-squark may be the natural consequence of a one-parameter string-inspired $SU(5) \times U(1)$ supergravity model [10], with the dilaton field being the dominant source of supersymmetry breaking [11], *and* the electroweak-size Higgs mixing parameter μ obtained naturally from supergravity-induced contributions [11, 12, 10].

Our model [10] is a special case of a generic supergravity model with universal soft supersymmetry breaking, which is described in terms of four parameters: $m_{1/2}, m_0, A, \tan\beta$. In the "special dilaton" scenario one has [11]

$$m_0 = \tfrac{1}{\sqrt{3}} m_{1/2}, \quad A = -m_{1/2}, \quad B = 2m_0, \tag{1}$$

where B is the soft-supersymmetry-breaking parameter (at the unification scale) associated with μ. These conditions determine all but one parameter, taken here to be $m_{1/2} \propto m_{\chi_1^\pm} \propto m_{\tilde{g}}$. The requirement of radiative electroweak symmetry breaking,[1] which determines μ up to a sign, can only be satisfied here for $\mu < 0$, in light of the last condition $B = 2m_0$. Moreover, this condition determines $\tan\beta$ as a function of $m_{1/2}$; one finds that $\tan\beta$ must be small: $\tan\beta \approx 1.4$, with little dependence on $m_{1/2}$ [10]. In what follows we take $m_t = 162 \, \text{GeV}$, i.e., the central value of the world-average fit to m_t ($m_t = 162 \pm 9 \, \text{GeV}$ [14]). (Details of the following analysis will appear elsewhere [15].)

For our present purposes, the main result, i.e., a light top-squark, is a consequence of the small value of $\tan\beta$. Indeed, the lightest top-squark mass is given by

$$
\begin{aligned}
m_{\tilde{t}_1}^2 =\ & \tfrac{1}{2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) + \tfrac{1}{4} M_Z^2 \cos 2\beta + m_t^2 \\
& - \sqrt{\left[\tfrac{1}{2}(m_{\tilde{t}_1}^2 - m_{\tilde{t}_R}^2) + \tfrac{1}{12}\cos 2\beta(8M_W^2 - 5M_Z^2)\right]^2 + m_t^2(A_t + \mu/\tan\beta)^2} \ ,
\end{aligned}
\tag{2}
$$

where $m_{\tilde{t}_{L,R}}^2$ are the running top-squark masses. In the present case there is a large cancellation between the first term $\tfrac{1}{2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)$ and the last term in the square root

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[1] For recent reviews of this general procedure see e.g., Ref. [13].

Table 1: Cross sections at the Tevatron (in pb) for $p\bar{p} \to \tilde{t}_1\bar{\tilde{t}}_1 X$ [5] and $p\bar{p} \to t\bar{t}X$ [19]. All masses in GeV.

$m_{\tilde{t}_1}$	70	80	90	100	112	m_t	120	140	160	180
$\sigma(\tilde{t}_1\bar{\tilde{t}}_1)$	60	30	15	8	4	$\sigma(t\bar{t})$	39	17	8	4

$m_t^2(A_t + \mu/\tan\beta)^2$, which leads to light top-squark masses, $i.e.$,

$$m_{\tilde{t}_1}^2 \sim \tfrac{1}{2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) + m_t^2 - m_t|A_t + \mu/\tan\beta| \ . \tag{3}$$

We find $m_{\tilde{t}_1} \gtrsim 67\,\text{GeV}$ ($c.f.$, the LEP limit $m_{\tilde{t}_1} > 45\,\text{GeV}$ [16]). (This result has a strong $\tan\beta$ dependence, $e.g.$, $m_{\tilde{t}_1} \gtrsim 90\,(120)\,\text{GeV}$ for $\tan\beta \approx 1.5\,(2.0)$, but here $\tan\beta$ is fixed and cannot be varied at will.) We also find $m_{\tilde{q}} \approx m_{\tilde{g}} \gtrsim 260\,\text{GeV}$, where $m_{\tilde{q}}$ is the average first- or second-generation squark mass. In Fig. 1 we present a collection of spectra plots versus the lightest chargino mass $(m_{\chi_1^\pm})$ for the lighter supersymmetric particles. We note in passing that in this model we find $B(b \to s\gamma) \approx (1-3) \times 10^{-4}$, which is in very good agreement with the present experimental results [17]. Also, the relic density of the lightest neutralino satisfies $\Omega_\chi h_0^2 \lesssim 0.85$, which is in natural agreement with cosmological observations and includes the possibility of a Universe with a cosmological constant [18].

The cross section for pair-production of the lightest top-squarks $\sigma(\tilde{t}_1\bar{\tilde{t}}_1)$ depends solely on $m_{\tilde{t}_1}$ [5] and is given for a sampling of values in Table 1. Since in this model $m_{\tilde{t}_1} > m_{\chi_1^\pm} + m_b$ (see Fig. 1), one gets $B(\tilde{t}_1 \to b\chi_1^\pm) = 1$. The charginos then decay leptonically or hadronically with branching fractions shown in Fig. 2, $i.e.$, $B(\chi_1^\pm \to \ell\nu_\ell\chi_1^0) \approx 0.4$ ($\ell = e + \mu$) for $m_{\chi_1^\pm} \lesssim 65\,\text{GeV} \leftrightarrow m_{\tilde{t}_1} \lesssim 100\,\text{GeV}$. The most promising signature for light top-squark detection is through the dilepton mode [7]. The number of stop-dileptons is:

$$N_{2\ell}^{\tilde{t}_1\bar{\tilde{t}}_1} = \sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times [B(\tilde{t}_1 \to b\chi_1^\pm)]^2 \times [B(\chi_1^\pm \to \ell\nu_\ell\chi_1^0)]^2 \times \mathcal{L} \approx 0.16\,\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \mathcal{L}. \tag{4}$$

The dilepton mode is also paramount in top-quark searches:

$$N_{2\ell}^{t\bar{t}} = \sigma(t\bar{t}) \times [B(t \to bW)]^2 \times [B(W \to \ell\nu_\ell)]^2 \times \mathcal{L} \approx 0.05\,\sigma(t\bar{t}) \times \mathcal{L}. \tag{5}$$

Here we have taken $B(t \to bW) = 1$, although one should account for the $t \to \tilde{t}_1\chi_1^0$ mode which is open also for light top-squarks. Moreover, $p\bar{p} \to t\bar{t}X \to \tilde{t}_1\bar{\tilde{t}}_1\chi_1^0\chi_1^0 X$ is another source of top-squarks, although much suppressed because of the small branching fraction: we find $B(t \to \tilde{t}_1\chi_1^0) \lesssim 10\%$. Combining Eqs. (4,5) we obtain

$$\frac{N_{2\ell}^{\tilde{t}_1\bar{\tilde{t}}_1}}{N_{2\ell}^{t\bar{t}}} \approx 3.2\frac{\sigma(\tilde{t}_1\bar{\tilde{t}}_1)}{\sigma(t\bar{t})} \ . \tag{6}$$

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Table 2: Upper limits on sparticle masses which follow from $m_{\tilde{t}_1} < 100\,\mathrm{GeV}$, such that $\tilde{t}_1$ may be relevant in top-quark searches. All masses in GeV.

$\chi_1^\pm$	χ_1^0	χ_2^0	h	$\tilde{e}_R$	$\tilde{\nu}$	$\tilde{e}_L$	$\tilde{t}_1$	$\tilde{b}_1$	$\tilde{q},\tilde{g}$
65	35	70	70	108	120	130	100	275	310

This ratio should open the eyes of experimenters because the number of observed dilepton events depends strongly on the experimental biases. This ratio (6) indicates that for sufficiently light top-squarks there may be a significant number of dilepton events of non–top-quark origin, if the experimental acceptances are tuned accordingly.

Perhaps the most important distinction between top-dileptons and stop-dileptons is their p_T distribution: the (harder) top-dileptons come from the two-body decay of the W boson, whereas the (softer) stop-dileptons come from the (usually) three-body decay of the chargino with masses (in this case) below m_W. Therefore, the top-dilepton data sample is essentially distinct from the stop-dilepton sample. Such distinction is well quantified by the "bigness" (B) parameter $B = |p_T(\ell^+)| + |p_T(\ell'^-)| + |\not{E}_T|$ of Ref. [7]. Another distinction between the two sources of dileptons are the b-jets, which are probably softer in the decay $\tilde{t}_1 \to b\chi_1^\pm$ (for light top-squarks) compared to those from $t \to bW$. The above discussion suggests that the CDF top-dilepton data sample should be carefully studied to see if softer stop-dileptons are present: an important new lower bound on the top-squark mass may follow. However, detailed simulations of the stop-dilepton signal and a re-analysis of the top-dilepton data are required before drawing more concrete conclusions.

We also note that in the ℓ+jets channel, the ratio analogous to Eq. (6) is $N_{\ell+\text{jets}}^{\tilde{t}_1\bar{\tilde{t}}_1}/N_{\ell+\text{jets}}^{t\bar{t}} \approx \sigma(\tilde{t}_1\bar{\tilde{t}}_1)/\sigma(t\bar{t})$, since $B(W \to 2j) \cdot B(W \to \ell) = (2/3)(2/9) \approx B(\chi_1^\pm \to 2j) \cdot B(\chi_1^\pm \to \ell)$ (see Fig. 2). In this case, the top-squark ℓ+jets events still have softer b-jets and a softer lepton.

The light top-squarks which may be relevant for the top-quark and top-squark searches at the Tevatron (*i.e.*, $m_{\tilde{t}_1} \lesssim 100\,\mathrm{GeV}$) entail a light supersymmetric spectrum, as can be seen from Fig. 1. For $m_{\tilde{t}_1} < 100\,\mathrm{GeV}$, we get the corresponding upper limits shown in Table 2. We now explore the possibilities for direct detection of these light sparticles at the Tevatron and LEPII.

- *Tevatron.* One could detect these light sparticles in three ways:

    - The trilepton signal in $p\bar{p} \to \chi_1^\pm\chi_2^0 X$ is the most promising avenue for detection of weakly interacting sparticles at the Tevatron [20, 21], as evidenced in the context of $SU(5) \times U(1)$ supergravity in Ref. [22]. The leptonic chargino and neutralino branching fractions are given in Fig. 2, and the trilepton rate at the 1.8 TeV Tevatron is given in Fig. 3, where we indicate by a dashed line the present CDF upper limit [23] and by a dotted line the expected reach by the end of Run IB (with $\sim 100\,\mathrm{pb}^{-1}$ of accumu-

lated data). This reach corresponds to $m_{\chi_1^\pm} \lesssim 80\,\text{GeV} \leftrightarrow m_{\tilde{t}_1} \lesssim 130\,\text{GeV}$. Therefore, the light sector of this model – that relevant to top-quark searches – could be definitively falsified in the next few months.

– Direct $\tilde{t}_1$ pair production at the Tevatron has been shown recently [7] to be sensitive to $m_{\tilde{t}_1} \lesssim 100\,\text{GeV}$ by the end of Run IB, provided the chargino leptonic branching fraction is taken to be $\sim 20\%$. For the chargino branching fractions in our model ($\sim 40\%$, see Fig. 2) the reach through the stop-dilepton channel is extended to $m_{\tilde{t}_1} \lesssim 130\,\text{GeV}$.

– The standard squark-gluino searches may also be able to reach up to $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 310\,\text{GeV}$ with the Run IB data.

• *LEPII.* One could detect these light sparticles in three ways:

– Charginos would be readily pair-produced, and best detected through the "mixed" mode (*i.e.*, $\ell + 2j$). For $m_{\chi_1^\pm} \lesssim 65\,(80)\,\text{GeV}$, we find $(\sigma \times B)_{\text{mixed}} \gtrsim 0.34\,(0.27)\,\text{pb}$, which is much larger than the estimated 5σ sensitivity at $100\,\text{pb}^{-1}$, *i.e.*, $0.12\,\text{pb}$ [24].

– The lightest Higgs boson should be easily detectable through the standard process $e^+e^- \to Z^* \to Zh$. For $m_h \lesssim 70\,\text{GeV}$ (from Table 2), we find a cross section in excess of $0.92\,\text{pb}$, which is much larger than the expected sensitivity limit of $0.2\,\text{pb}$ for a 3σ effect at $500\,\text{pb}^{-1}$ [25]. In fact, a $0.92\,\text{pb}$ signal corresponds to a significance of 6.2σ at $100\,\text{pb}^{-1}$.

– The light top-squark may also be produced directly $e^+e^- \to \tilde{t}_1 \bar{\tilde{t}}_1$ via s-channel γ, Z exchange, and be probed up to $m_{\tilde{t}_1} \approx \sqrt{s}/2 \approx 100\,\text{GeV}$.

In summary, we have discussed the prediction of a light top-squark in a string-inspired one-parameter $SU(5) \times U(1)$ supergravity model. This sparticle ($\tilde{t}_1$) may be readily pair-produced at the Tevatron and, if $m_{\tilde{t}_1} \lesssim 130\,\text{GeV}$, even be observed with the present run accumulated data. Top-squark production may also be an important source of sought-for top-quark signatures in the dilepton and ℓ+jets channels. Therefore, a re-analysis of the top data sample in the presence of a possibly light top-squark appears necessary before definitive statements concerning the discovery of the top quark can be made. Another prediction of this model is a direct link between the light top-squark and a light supersymmetric spectrum, which can certainly be searched for at the Tevatron through trilepton and squark-gluino searches, and at LEPII through direct $\tilde{t}_1$ pair-production (for $m_{\tilde{t}_1} \lesssim 100\,\text{GeV}$) and via chargino and Higgs-boson searches.

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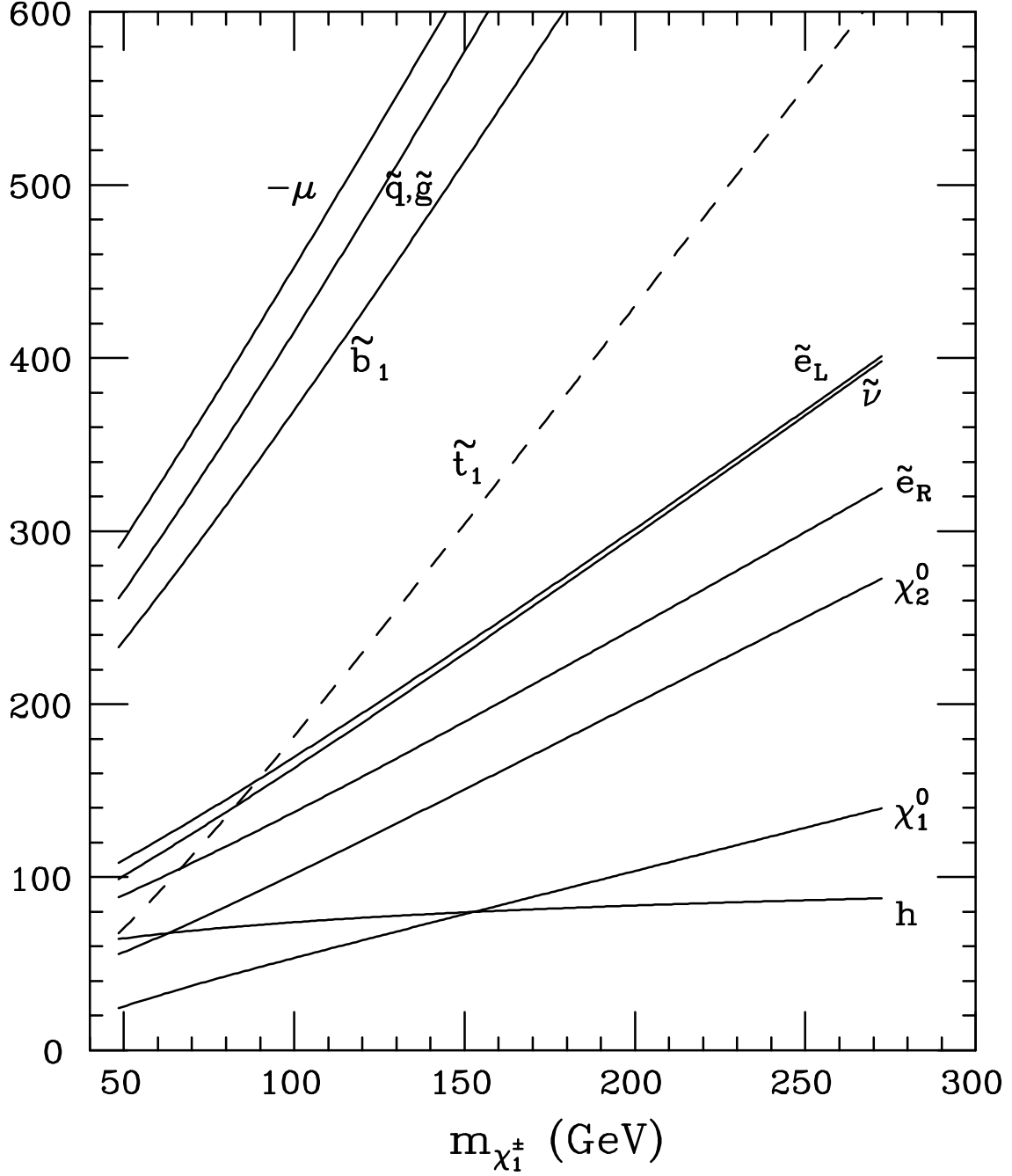
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Figure 1: The relevant lighter sparticle masses versus the chargino mass. The $\tilde{t}_1$ top-squark mass (with $m_{\tilde{t}_1} > 67\,\mathrm{GeV}$) is shown by the dashed line. Note that $m_{\tilde{t}_1} > m_{\chi_1^\pm}$. Here $m_{\tilde{q}} \approx m_{\tilde{g}}$, with $m_{\tilde{q}}$ the average first- or second-generation squark mass. Also, $m_{\chi_2^0} \approx m_{\chi_1^\pm} \approx 2m_{\chi_1^0}$, and $m_A \approx m_H \approx m_{H^\pm} > 400\,\mathrm{GeV}$.
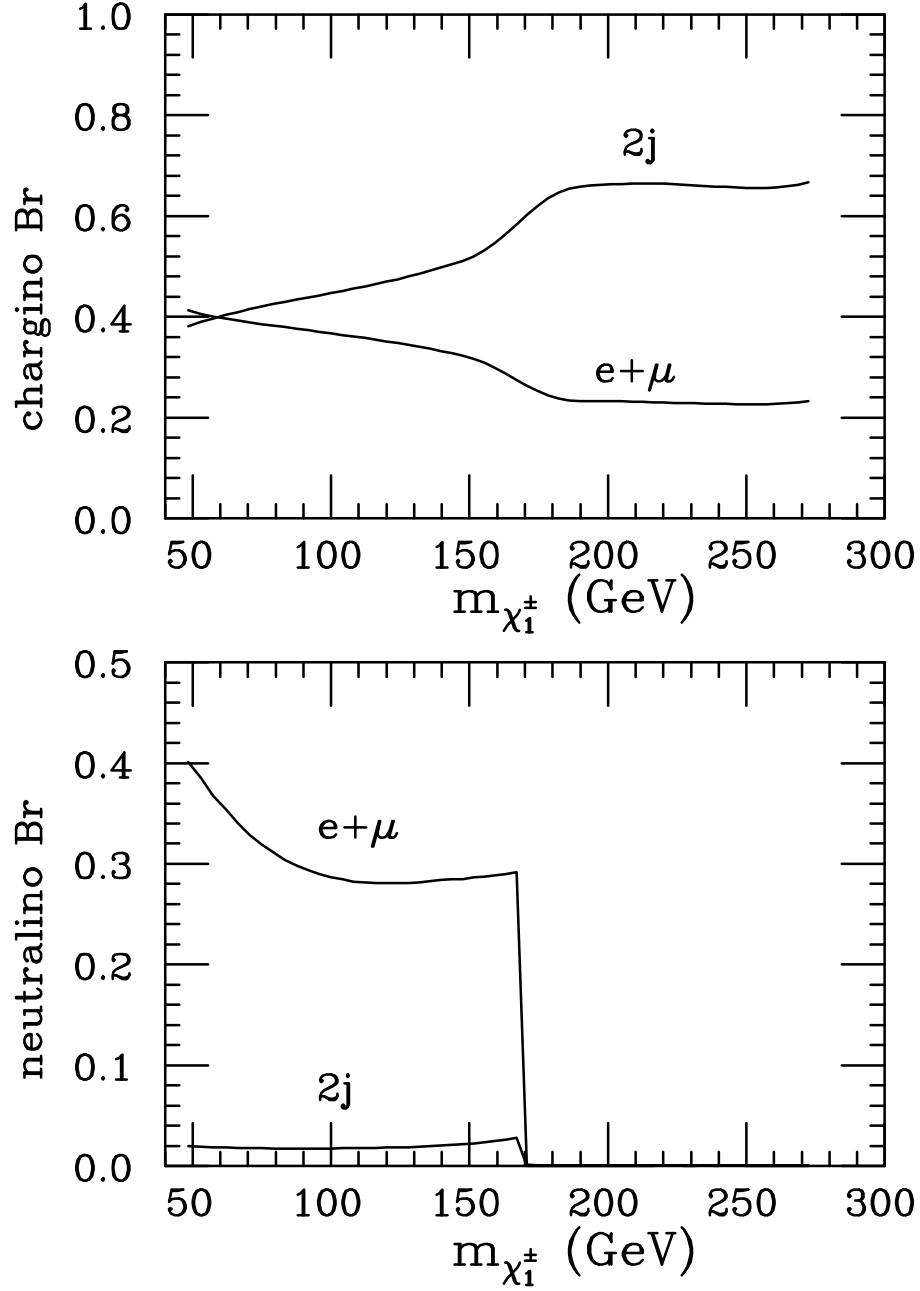
Figure 2: The leptonic and hadronic branching fractions of the chargino ($\chi_1^\pm$) and the neutralino (χ_2^0) (other channels are not shown). The sudden drop in the leptonic neutralino branching ratio at $m_{\chi_1^\pm} \approx 170\,\text{GeV}$ corresponds to the opening of the "spoiler mode" $\chi_2^0 \to \chi_1^0 + h$.
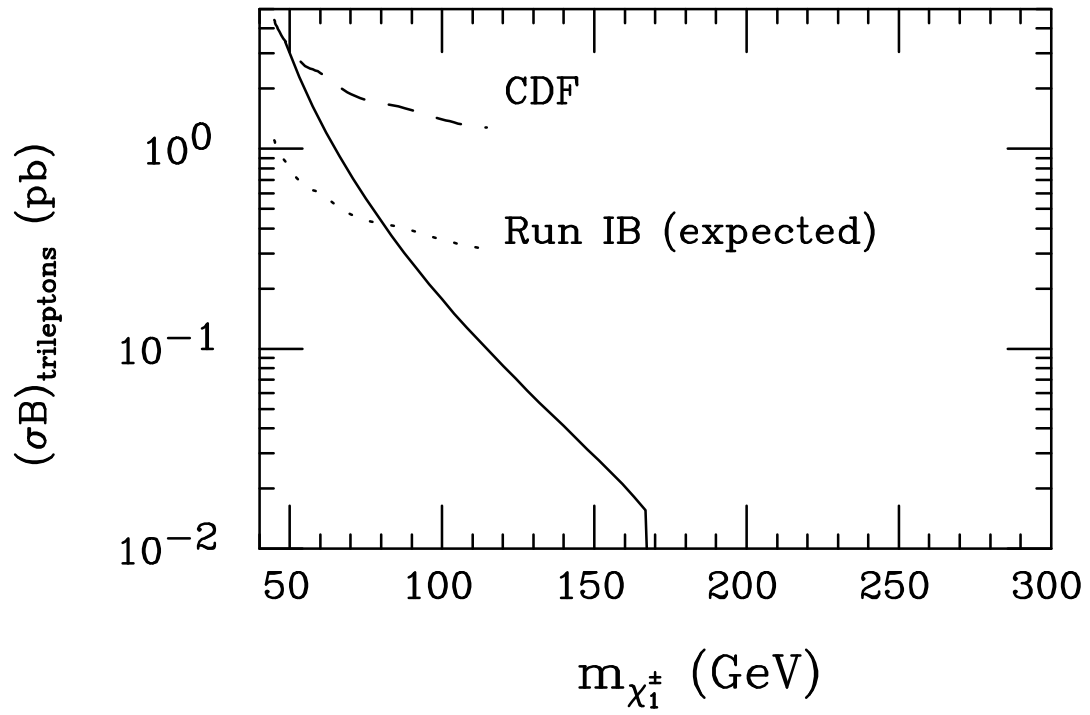
Tevatron

Figure 3: The rate for trilepton events at the Tevatron. The present CDF limit is indicated. The dotted line indicates the expected sensitivity at the end of Run IB ($\sim 100\,\mathrm{pb}^{-1}$) equivalent to a reach $m_{\chi_1^\pm} < 80\,\mathrm{GeV}$.